CASSINI RADAR/RADIOMETER AND VLA OBSERVATIONS OF JUPITER'S SYNCHROTRON EMISSION

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Abstract

We present observations of Jupiter's synchrotron emission made jointly from the Earth and from the Cassini spacecraft as it recently flew past Jupiter. These include observations at the lowest and highest frequencies ever used to image this emission, which thereby provide new and unique information on the Jovian electron energy spectrum. In particular, the Cassini Radar instrument includes a passive radiometer operating at 2.2–cm wavelength that clearly detected synchrotron emission as evidenced by its polarization and spatial distribution, even though it amounted to only about 1.1% of the total emission from Jupiter. We conclude from this result that the population of electrons with energies in excess of about 20 MeV is several times less than expected based on the best current model.

1 Introduction

Around New Year's 2001, the Cassini spacecraft flew past Jupiter en route to Saturn and provided an opportunity to observe the Jovian synchrotron radiation using the radiometer subsystem of the Cassini RADAR instrument. The Jovian synchrotron emission becomes relatively weak compared to thermal emission from the planet itself at wavelengths shorter than about 6 cm. Earth–based radio telescopes have not been able to determine the

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synchrotron radiation in the vicinity of the 2.2–cm wavelength of the Cassini radiometer, or shorter, because of the difficulty in separating Jupiter's atmospheric thermal emission from the synchrotron radiation. Hence the Jupiter flyby provided a unique opportunity to observe this emission. At the same time as the space observations, we conducted a ground–based campaign to observe the synchrotron radiation at a variety of wavelengths using the Very Large Array of the National Radio Observatory and the NASA's Deep Space Network antennas. The resulting data cover a range of frequencies that include the lowest and highest frequencies ever used to image Jupiter's synchrotron emission. The data thus provide unique information on both the distribution and the energy spectrum, particularly at the highest energies, of the energetic electrons in the Jovian magnetosphere. Results from the Cassini RADAR instrument and the VLA are presented here, while the DSN and Goldstone Apple Valley Radio Telescope (GAVRT) results are given in a companion paper [Klein et al., 2001].

2 VLA measurements

We observed the synchrotron radiation on January 3, 2001 at 20 and 90 cm (1.5 GHz and 325 MHz) using the VLA. On this date the VLA was in its "A" configuration, which is the configuration that uses the full 36–km extent of the array. The synthesized beamwidth (HPBW) was approximately 6 arc sec at 90 cm and 1 arc sec at 20 cm. The 11–hour duration of the observations allowed us to cover one full rotation of Jupiter and image the synchrotron emission in snapshot mode at all longitudes. All four Stokes parameters were measured, although here we present only the images of total intensity, converted to brightness temperature.

Figure 1 shows the emission imaged at 40° intervals in CML at both wavelengths. A model of the disk has been subtracted from these images, which were further adjusted to a standard orientation and distance of 4.04 AU.

Figure 2 shows the emission averaged over the complete rotation at each wavelength. These averages can be somewhat misleading because the particle distribution and resulting radiation is strongly asymmetric and varies significantly with CML; however, they are useful to compare with the similarly averaged 2.2–cm emission presented here. The total synchrotron emission adjusted to 4.04 AU was determined to be 5.5 $\pm$ 0.5 Jy at 20 cm and 5.15 $\pm$ 0.7 Jy at 90 cm.

3 Cassini RADAR/Radiometer observations

Measurements of the Jovian microwave emission at a wavelength of 2.2 cm were successfully carried out on January 3, 2001, near the time of closest approach to Jupiter. The radiometer is an integral component of the Cassini RADAR instrument [Elachi, 2001] with the characteristics summarized in Table 1. Its principal objective is to support the RADAR objectives of characterizing the surface of Saturn's satellite Titan, although its capabilities as a passive remote sensing instrument allow it to address a wide range of a)

b)

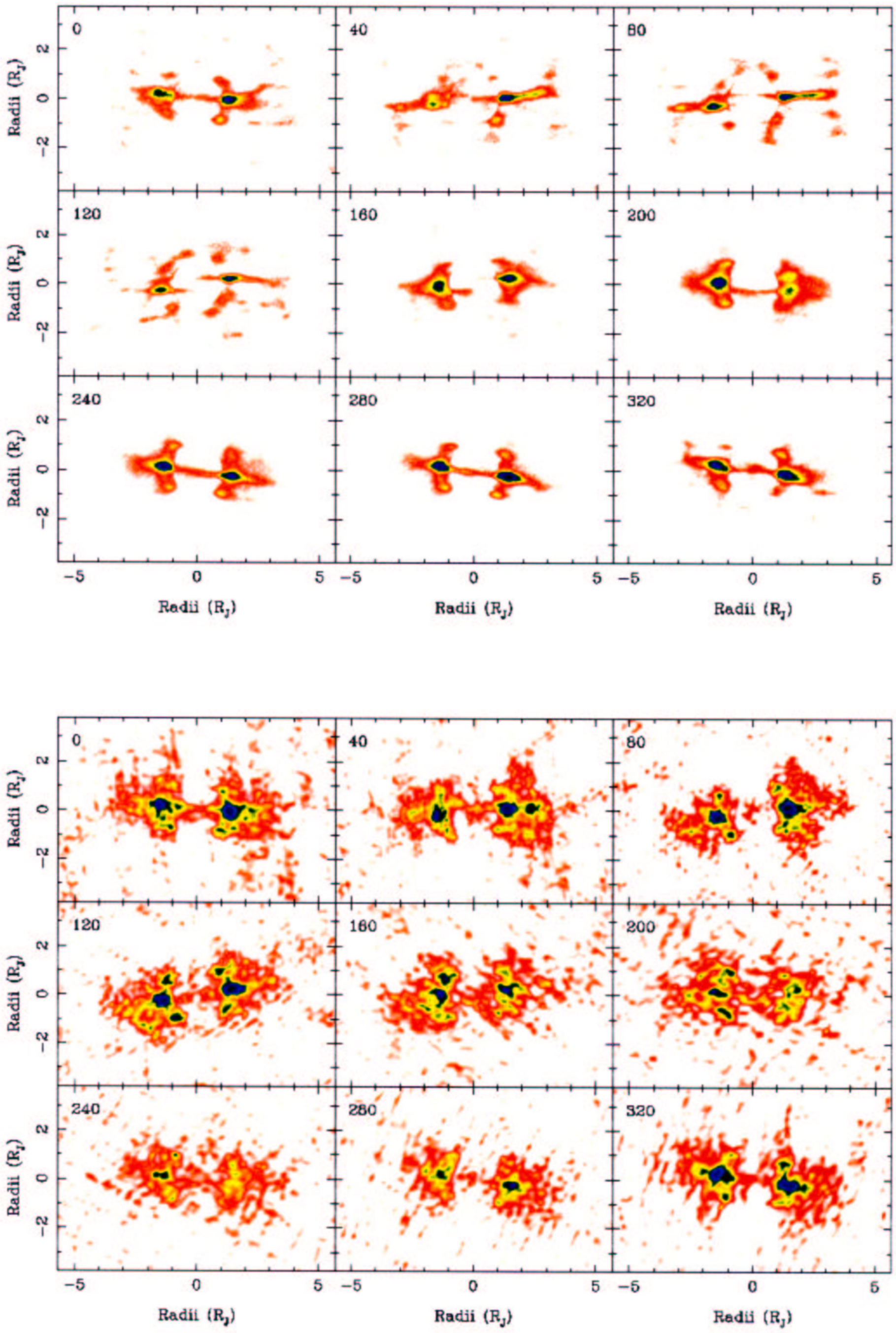
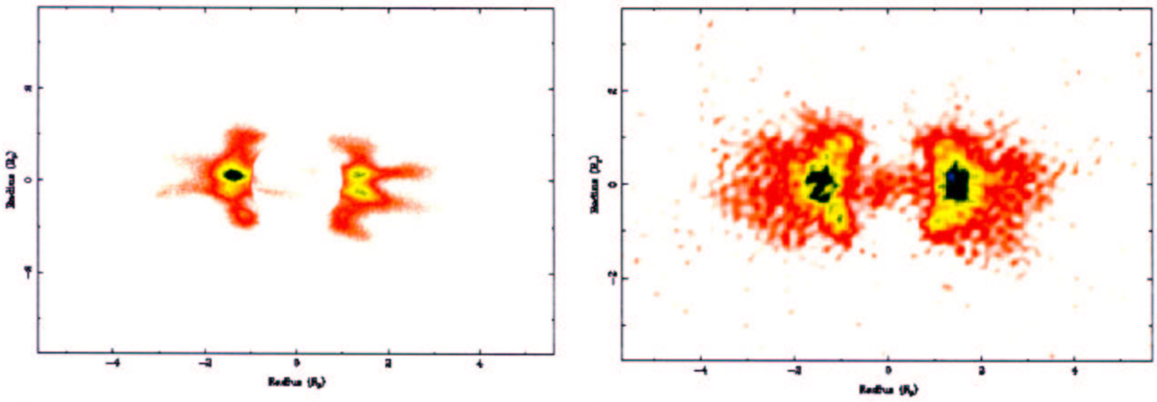


Figure 1: VLA Observations of Jupiter's synchrotron emission. Observations are shown averaged over 40–degree CML intervals. A model of the disk has been removed. a) Observations at 20–cm wavelength; b) Observations at 90–cm wavelength.

secondary objectives. The radar and radiometer use the spacecraft's main communication antenna, a 4–meter on–axis Cassegrain reflector. It receives one linear polarization whose sense is fixed in the Cassini spacecraft frame–the orthogonal polarization is obtained by



a) b)

Figure 2: VLA Observations of Jupiter's synchrotron emission averaged over all CMLs. a) Observations at 20–cm wavelength; b) Observations at 90–cm wavelength.

Table 1: Cassini RADAR/Radiometer Characteristics

Frequency	13.78 GHz
Wavelength	2.18 cm
1–sec noise	0.025 K
Half–Power Beamwidth	0.35°

repeating a given observation with a 90° rotation of the spacecraft.

Jupiter was imaged by raster scans as illustrated in Figure 3 and described in the caption. The rectangular pattern was sized to cover the expected extent of the belt emission with sufficient leeway on all four sides to ensure a good cold sky reference for each raster. Twenty such scans were obtained over a period of approximately 20 hours, ten at each of the two orthogonal linear polarizations aligned with Jupiter's axes. The maps covered two complete rotations of Jupiter, one in each polarization.

Maps of the synchrotron emission component required detailed accounting for the disk thermal emission and the radiometer beam pattern. Our procedure assumed we had full knowledge of the beam pattern and the disk thermal brightness distribution, and the synchrotron emission was obtained as the residual of a best fit of the beam–convolved disk brightness to the observations.

The beam pattern was determined as a composite of raster scans of the sun and Jupiter (using the same technique as for Jupiter shown in Figure 3) obtained prior to the flyby. The sun presents a bright, nearly point source that is measurable over nearly four orders of magnitude in amplitude, although it saturated the radiometer above approximately the beam half–power point. A similar raster scan of Jupiter made when Jupiter was less than 0.1° in diameter as seen from the spacecraft was used to fill in the central peak of

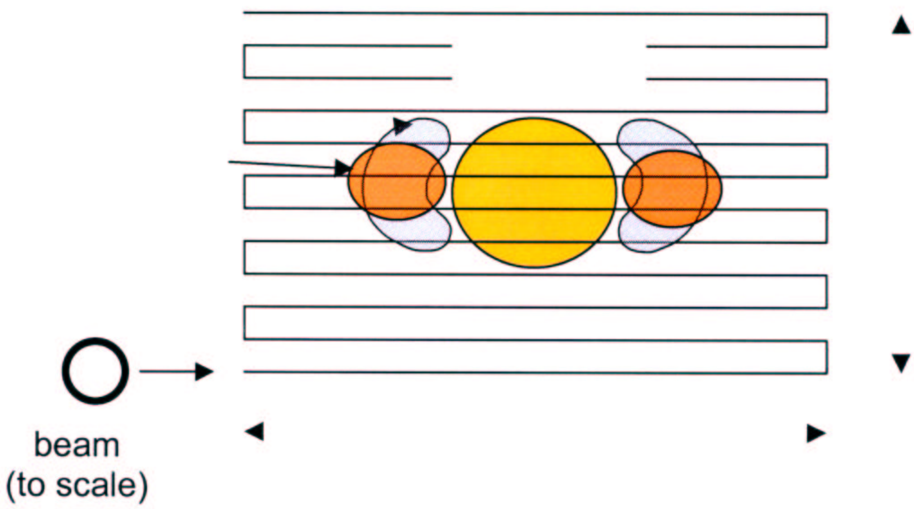


Figure 3: Raster scan pattern for Cassini radiometer observation of Jupiter. The planet, radiometer half–power beamwidth, scan pattern, and Jupiter are shown approximately to scale. A single scan sequence is indicated and shows 12 rasters separated by 0.18°, or approximately 1/2 beamwidth. Each such scan took just under one hour to complete. The polarization was aligned either with Jupiter's equator or pole. The expected spatial distribution of Jupiter's synchrotron emission is shown schematically. The emission is expected to be concentrated toward the equatorial plane when the polarization is aligned with Jupiter's pole (red shading), and distributed towards higher latitudes (blue shading) when the polarization is aligned with the equator.

the beam. Small corrections were necessary to account for the finite sizes of the sun and Jupiter at the times of observation. The resulting pattern is shown in Figure 4. The pattern agrees well with prelaunch measurements of the antenna at levels down to 25 dB below the central peak. The half–power beamwidth agrees in both axes to better than 1 percent with these measurements. We estimate the pattern obtained by scanning is correct to about the 30 dB level, where the uncertainty approaches 50%. Its principal lack for the purpose of this study is the limited angular range of the scan pattern ($3° \times 3°$), which failed to cover the measurable extent of the sidelobes.

The brightness distribution across Jupiter's disk was determined from a radiative transfer calculation for a nominal model of Jupiter's atmosphere. Jupiter's brightness at wavelengths in the vicinity of the 24–GHz ammonia absorption band originates in the ammonia cloud saturation region around the 150 K temperature level. The atmospheric physical and ammonia concentration profiles and the ammonia absorption coefficient are sufficiently well known to predict a reliable average brightness distribution. The main source of uncertainty is expected to be brightness variations across the belts and zones due to variations in ammonia concentration in the ammonia saturation region. Variations of a few Kelvin associated with these features have been observed by the VLA [de Pater et al., 1986].

The scan data were analyzed to account for gain and baseline drifts, as well as spacecraft pointing offsets and their stability. Linear baseline drifts in the antenna temperature

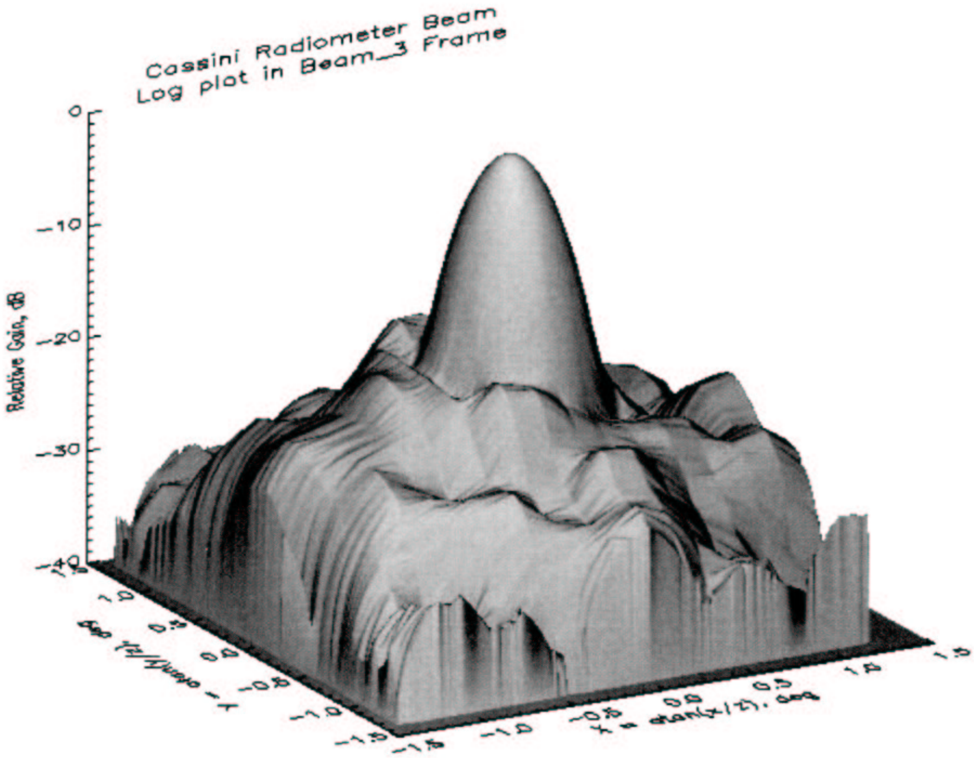


Figure 4: Gain pattern of the Cassini radiometer beam. The pattern was determined as a composite of data obtained from scans across the Sun and Jupiter as described in the text.

(offsets relative to cold sky) in each scan line of each frame were removed from the time–ordered data using the cold sky determinations at the beginning and end of each scan line. The convolved Jupiter disk model was then fit to each data frame. The fit included determination of the disk amplitude and the spacecraft pointing offset. Receiver gain drift was monitored by the determination of disk amplitude for each frame, which should remain nearly constant. The maps shown in the following are the polarization–averaged residuals to this fitting. Success of this procedure was due in large part to the stability of the radiometer and the spacecraft: gain and pointing were seen to vary to less than 1% and 0.02 mrad respectively over the entire 20–hour period of the observations.

Synchrotron emission, although even weaker than anticipated, was clearly detected distinct from the thermal emission as evidenced by its polarization and spatial distribution. Figure 5A shows the fit residuals averaged over 10 hours at each polarization. Figure 5B shows a calculation of the expected emission at 2.2 cm using a model based on previous VLA observations at 20–cm wavelength (see discussion below). Although the polarized signals predicted by the model is a factor of several greater than the residual maps, the relative distributions and amplitudes of the residuals agree well with those predicted. We have estimated the total synchrotron emission by averaging these residuals over both polarizations (see Figure 6), finding that they amount to about 1.1 ± 0.5% of the disk

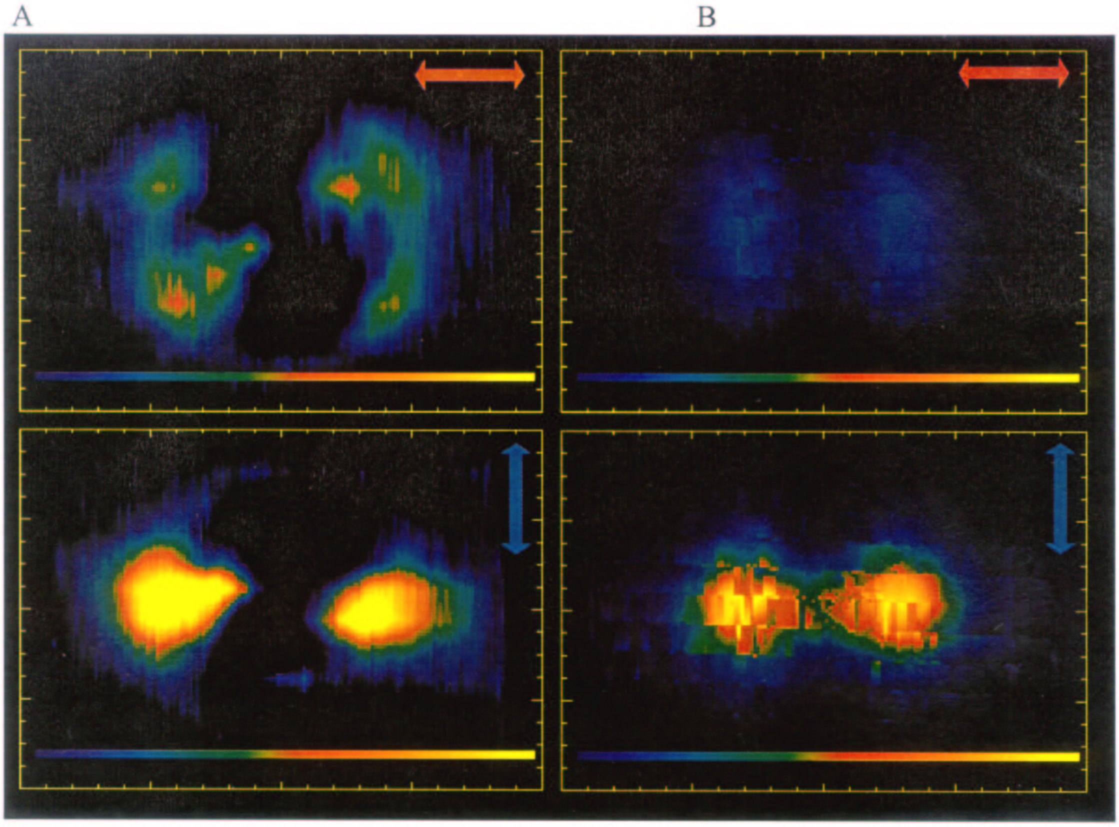


Figure 5: Polarized synchrotron emission at 2 cm. A) Measured as residuals to a least–squares fit of a model disk brightness distribution to the Cassini radiometer data; B) Computed from a model based on previous VLA 20–cm data.

emission. This translates to a total flux of 0.44 ± 0.2 Jy adjusted to a standard distance of 4.04 AU.

4 Comparison with models and conclusions

We expect to obtain a much more complete picture of the energy spectrum and distribution of relativistic electrons trapped in Jupiter's radiation belts by combining these data and incorporating previous ground based measurements. We extended a synchrotron emission model that we developed based on previous 20–cm VLA observations [Levin et al., 2001] to simulate the Cassini observations, including polarization, longitudinal averaging, geometric perspective from the spacecraft, and smoothing by the antenna gain pattern. The extrapolation to 2–cm wavelength is dependent on the assumption of an electron energy distribution, and is particularly sensitive to the population of electrons in the highest energy range; i.e., to those electrons with energies in excess of 20 MeV. The order–of–magnitude drop in flux at 2 cm compared to the 90 and 20–cm results reported here indicates a significant drop in this high–energy electron population. Some fall–off

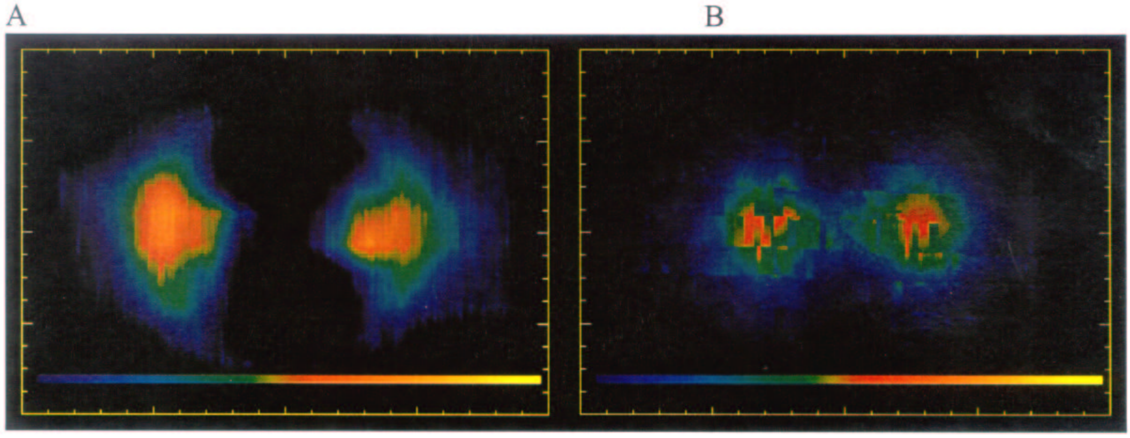


Figure 6: Synchrotron total emission. A and B as in Figure 5.

has been anticipated [Divine and Garrett, 1983]; however, our preliminary conclusion is that these electrons are yet several times less populous than expected.

We have reported preliminary results here, and work remains to calibrate and analyze the data. In particular, we are scheduled to obtain a Sun scan over the measurable extent of our beam sidelobes. Uncertainty in our knowledge of these sidelobes is presently our main source of uncertainty in interpreting the residuals from our fitting procedure. Along with using an improved beam pattern, we will fit the synchrotron emission model directly in our procedure. The residuals obtained after fitting both the disk and synchrotron model will give us a better determination of the model's characteristics as well as the uncertainties in this procedure.

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